

Consistency of human brain response to noisy visual inputs

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Abstract—We investigate the “consistency” of human brain response to repeatedly presented noisy visual inputs. We applied canonical correlation analysis to evaluate consistency of EEG signals between trials. We have found significantly higher canonical correlations between EEG datasets for the presentation of same visual noise realizations than for the presentation of different noise realizations. We speculate that the human brain, which is a high-dimensional nonlinear system, shows consistency in responses, which plays a functional role in robust information processing in a noisy environment.

1. Introduction

“Consistency” is defined as the reproducibility of response waveforms of a nonlinear dynamical system driven by a same input signal, starting from different initial conditions of the system [8]. Previous studies have shown consistency of response outputs in laser systems [8], dynamical systems [8, 9], and single neurons [3].

It has not been known, however, whether the human brain, which is a high-dimensional nonlinear dynamical system, shows a signature of consistency. We therefore investigate whether the human brain responses to noisy visual inputs, measured by electroencephalography (EEG), show the signature of consistency.

The concept of consistency of human brain responses is shown in Figure 1. To investigate the consistency of brain responses, we used canonical correlation analysis (CCA). CCA is a conventional method to extract linear combinations of data variables which have maximal correlations between two datasets. The method was first introduced by Hotelling in 1936 [2]. CCA has been applied to the analyses of nonlinear dynamical systems e.g. for analyzing synchronization between chaotic signals [5] and movement of robots [6, 7].

Specifically, we analyzed whether 63ch EEG signals, when participants are repeatedly presented with an identical realization of noisy visual signal, indicate high canonical correlations across trials.

2. Methods

2.1. Experimental procedures

We analyzed data obtained from three right-handed healthy participants who gave informed consent. The study was approved by the ethical committee of RIKEN. Participants were required to look at a fixation cross while presented with flickering checkerboard stimuli on a CRT monitor whose refresh rate is 60 Hz. A chin rest was used

to fix participants’ head position through the experiment. Participants were instructed to avoid making eye blinks and eye movements while the visual stimuli are presented.

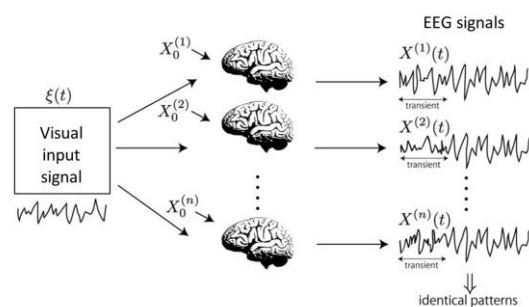


Figure 1: Consistency of human brain responses. A visual input signal $\xi(t)$ is repeatedly presented to the brain of a single subject with different initial states $X_0^{(n)}$. We investigate if brain responses $X^{(n)}(t)$ measured by EEG signals show consistency across different trials.

The checkerboard stimuli were consisted of 25 gray squares whose gray level is modulated in a Gaussian white noise way (Figure 2). The average gray level was 128 and the gray levels of brighter and darker squares were counter phase modulated at a frame rate of 30 Hz. The flickering stimuli were presented for 8 seconds. We used 5 different noise intensity levels. The SD of the Gaussian noise was 2,4,6,8, or 10. Two different time series realizations were used at each noise intensity level. 10 trials were presented for each realization at each noise intensity.

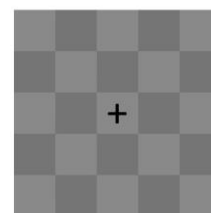


Figure 2: Noisy checkerboard stimulus

2.2. EEG measurements and preprocessing

63ch EEG signals were recorded at a sampling frequency of 1000 Hz using an EEG amplifier (BrainAmp MR plus, Germany). First, EEG signals were offline re-referenced to the averaged signals from right and left earlobes. Next, an ICA-based automatic artifact removal procedure was applied to EEG signals [1][4]. Finally, we applied a band-pass filter to the 63ch EEG signals between 2 and 100 Hz.

2.3 CCA

We analyzed preprocessed 63ch EEG signals from 0 to 7 sec after the onset of noisy visual stimuli using CCA.

Given two random EEG vectors \mathbf{x} and \mathbf{y} , where the state vector of one observation is denoted by $\mathbf{x} \in \mathbf{X} \subset \mathbb{R}^D$, and the state vector of the other observation is denoted by $\mathbf{y} \in \mathbf{Y} \subset \mathbb{R}^D$, where D is the number of electrodes ($D=63$). We have T samples of \mathbf{x} and \mathbf{y} , where T is the number of time points ($T=7000$). CCA derives the directions \mathbf{w}_X and \mathbf{w}_Y such that the correlation between the two projected random variables $\mathbf{w}_X^T \mathbf{x}$ and $\mathbf{w}_Y^T \mathbf{y}$ is maximized. This optimization problem can be solved by finding eigenvectors for a generalized eigenvalue problem [6, 7].

Since there are 10 trials for each of two realizations at each noise intensity level, namely, there are 100 combinations of pairwise datasets (\mathbf{X} and \mathbf{Y} are single trial EEG datasets consisted of 63ch*7000 time points) between different visual noise realizations and 90 combinations of datasets between same noise realizations, respectively. We applied CCA between these pairwise EEG datasets and evaluated the averaged maximal canonical correlations across all combinations.

We also conducted CCA between the time series data of visual noise (1ch*7000 time points) and EEG datasets (63ch*7000 time points). In this case, there are 20 combinations for same (corresponding) realizations and 20 combinations for different (the other) realizations of visual noise and EEG datasets.

3. Results and discussion

Figure 3 shows the averaged canonical correlation coefficients between EEG datasets for same and different visual noise realizations. We found significantly higher averaged canonical correlations between the same realizations than between different realizations ($p < 0.05$, unpaired Student's t-test, Bonferroni-corrected) except for lower noise intensity conditions in subject 1. The results indicate that EEG responses to identical noisy visual inputs show consistency across trials.

Figure 4 indicates canonical correlation coefficients between visual noise signals and EEG signals. There were no significant differences between same and different combinations in most cases except for the highest noise intensity condition in subject 3. The results suggest that consistency of EEG responses observed in the case of same visual noise realizations is not simply explained by the linear transformation of visual noise realizations.

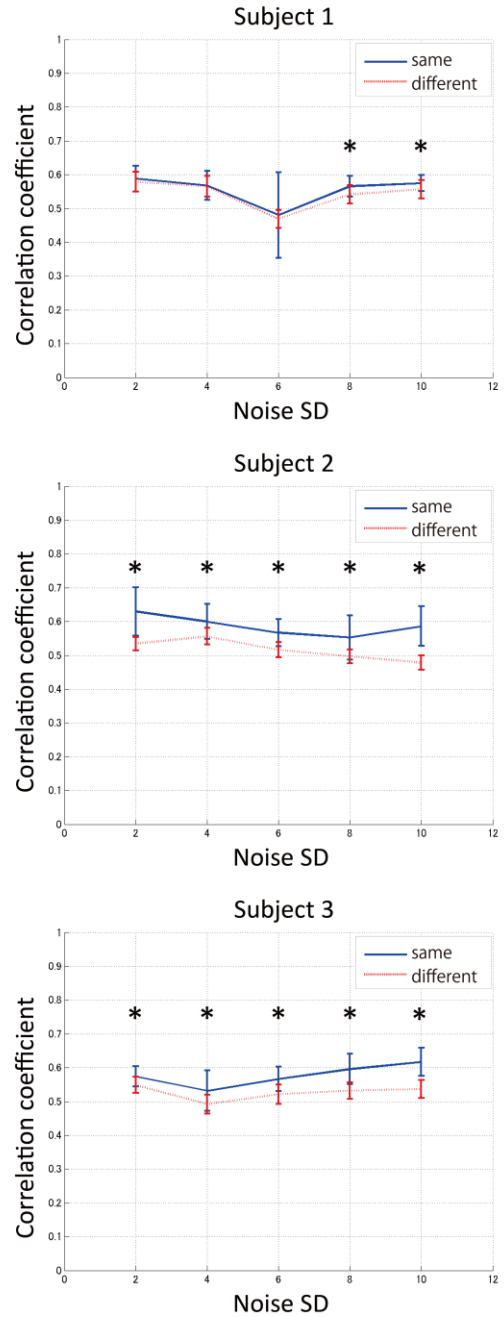


Figure 3: Averaged canonical correlation coefficients of EEG responses between trials from different and same visual noise realizations. Data are shown for 3 subjects as a function of noise intensity. Error bars indicate standard deviation. Asterisks indicate significant difference ($p < 0.05$) between same and different realizations.

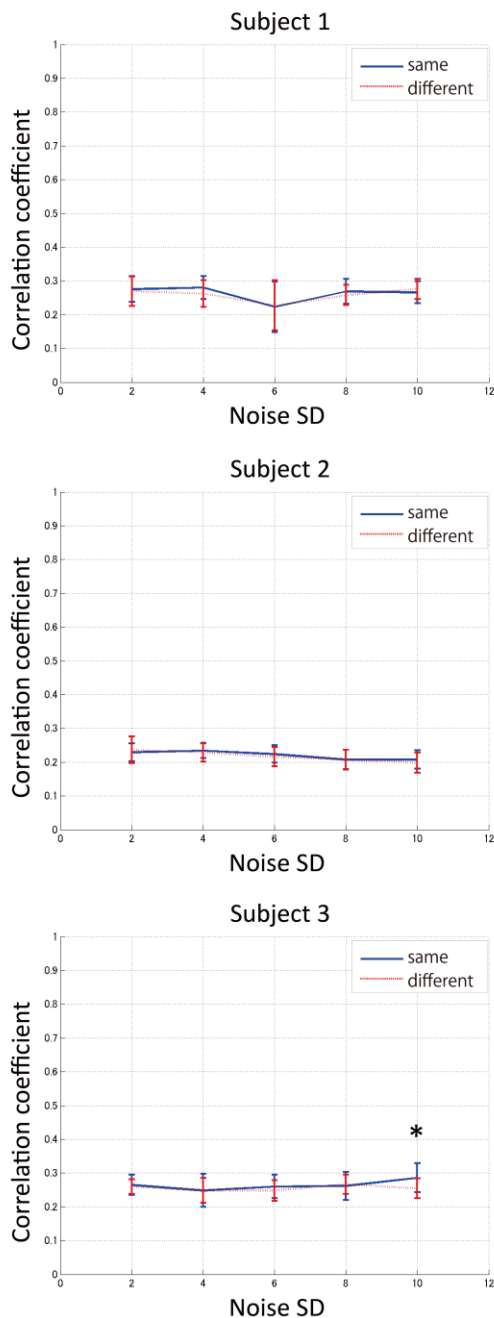


Figure 4: Averaged canonical correlation coefficients between visual signals and EEG responses for trials from different and same visual noise realizations. Error bars indicate standard deviation. Asterisk indicates significant difference ($p < 0.05$) between same and different realizations.

Taken together, we provide first evidence that human brain responses measured by EEG exhibit a signature of consistency to identical noisy visual inputs. We speculate that human brain, which is a high-dimensional nonlinear system, shows the characteristics of consistency, which plays a functional role in robust information processing in a noisy environment. We propose that CCA is a good

approach to analyze consistency of multivariate signals from complex systems such as the human brain.

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